A Ph.D. SYNOPSIS

Research Area: **Power System**

On the topic of

Soft Computing Optimization Techniques for some Unit Commitment Models in Power System

Submitted by

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1. Introduction

The Unit Commitment (UC) is an important step in scheduling and dispatching of electric power [1] usually covering the scope of hourly power system operation decisions with a one-day to one week horizon. A simple power system may be considered as generating units coupled at one end and consumer load at the other end as shown in Fig. 1.

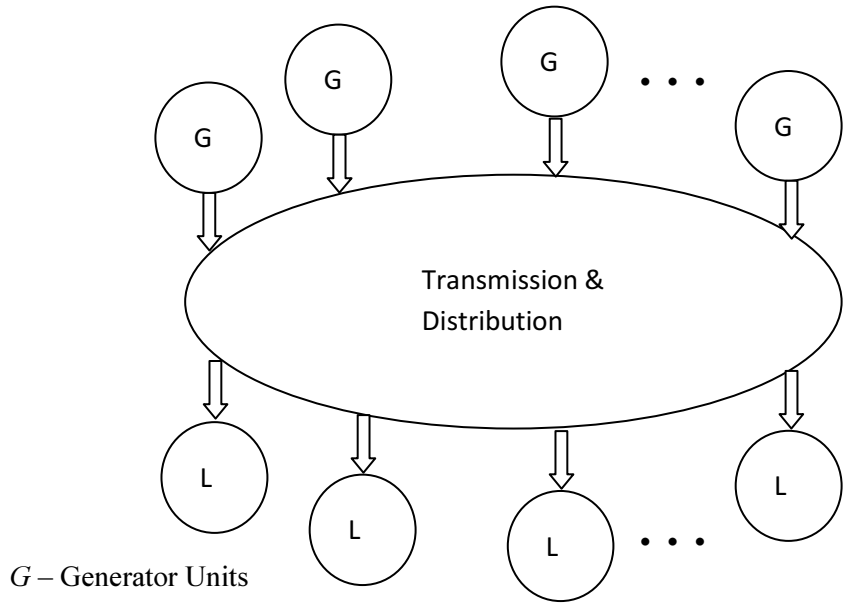

Fig. 1 A Simple Power System

A planning activity is essential as system demand keeps on varying throughout a day or a week. It is uneconomical to keep all the units on-line for the entire duration [2]. The generation cost can be saved to great extent if generating units start up or shut down according to proper schedule. UC provides a proper coordination between generating power and its demand.

UC activity is carried out in advance as thermal generating units can not start and produce power all of sudden. UC ensures that sufficient generation capacity is always available to cope up system demand plus reserve margin in case of outage of generators or transmission lines or load demand increment. The schedule of generating units is decided by UC to minimize operating cost and satisfy load demand and system requirements for certain time intervals. The focus of conventional UC is to determine startup and shutdown schedules of thermal units to meet load demand of certain time interval (24h to 1 week). The conventional UC belongs to a class of combinatorial optimization problems.

Shortly after power system restructuring, a Price based UC model (PBUC) (occasionally referred to as Profit based UC) different from conventional UC is preferred for power markets due to power supply-side biddings. The distinct feature of PBUC is that all market information is reflected in market price. The optimal solution of this complex optimization problem of energy market is useful to discover opportunities of arbitrage and the valuation of generation assets. Another important UC model, Security constrained UC (SCUC) determines an optimal schedule while ensuring its feasibility based on constraints of transmission network.

The above mentioned UC models are large scale optimization problems that determine the operating status of large number of generating units based on a set of complicated constraints. UC has become a major research in power systems area in the past few decades due to the scale of the problem and the frequency at which it must be solved.

The reasons such as large variation between peak and off-peak power load, complexity of starting and restarting of modern generating facilities in current time, start-up, shut-down time and dynamic considerations in comparison to smaller older units motivate us to devolve new optimization techniques. Automated computerized schedulers are required for new generating units because conventional techniques are not able to provide adequate results over hybrid soft-computing techniques.

2. Different Unit Commitment Models

The main features and significance of same UC models as mentioned in previous section are discussed below.

2.1 Conventional Unit Commitment

Conventional UC aims to schedule the most cost-effective combination of generating units to meet forecasted load and reserve requirements. Constraints such as system power balance, system spinning reserve, and unit's minimum up and down times are also satisfied.

2.1.1 Objective Function

The ON/OFF switching schedule of generating units for every one hour duration over a day or a week period is prepared to meet the system demand and spinning reserve at minimum composite production cost while satisfying all unit and system constraints. The following cost components are considered in composite production cost function.

i) ***Fuel Cost-*** The convex shaped function used for operating fuel cost equation for unit *i* and is mathematically represented as:

$$C_i(P_i) = \sum_{i=1}^{N}\left[a_i P_i^2 + b_i P_i + c_i\right] \quad \text{(Units without valve point effects)}$$

Non convex characteristic is obtained due to valve point effect. The effects of valve points are taken by adding a sinusoidal function to the convex cost function and represented as:

$$C_i(P_i) = \sum_{i=1}^{N}\left[a_i P_i^2 + b_i P_i + c_i + \left|e_i \sin f_i\left(P_{i_{min}} - P_i\right)\right|\right] \text{ (Units with valve point effects)}$$

ii) ***Start up cost-*** This component is included to consider generator start-up operation cost. This is often modelled as a function of the time for which the unit remained off-line.

$$ST_i = \alpha_i + \beta_i(1 - e^{-\frac{T_i^{OFF}}{\tau_i}})$$

α is fixed cost associated with the unit start-up, β is the cost involved in a cold start-up, T^{OFF} is the time for which the unit has been off and τ is a time constant representing the cooling speed of the unit.

iii) ***Shut down cost-*** Although other cost components are more significant than this component but a fixed cost representation is used in composite production cost given as follows.

$$SDi = KPi$$

where *K* is the incremental shut-down cost.

iv) ***Composite production cost function-*** For conventional UC problem, composite production cost function is formed as

$$J = \sum_{k=i}^{T}\left[C_{i,k}\left(P_{i,k}\right).W_{i,k} + ST_{i,k}.UST_{i,k} + SD_{i,k}.USD_{i,k}\right]$$

UST, *USD* and *W* are integer decision variables denoting the status of the unit at hour *k*. W denotes the unit status (1=running, 0=off), *UST* denotes the unit start-up state (1=start-up, 0=no start-up) and *USD* denotes the unit shut down state (1=shut down, 0=no shut-down).

2.1.2 Constraints

UC problem is subjected to many constraints that include:

i) ***Demand-Supply Balance and Spinning Reserves constraint-*** It ensures enough generation capacity (including any pre-decided import or export contracts with other utilities) for a particular hour so that the demand at that hour and spinning reserve are met.

ii) ***Generation limits-*** The loading of each generating unit must be within its minimum and maximum permissible rating (limits).

iii) ***Minimum Up and Down Time Constraints on Thermal Units-*** These constraints for large thermal unit must be satisfied in order to ensure the minimum number of hours a unit must be on, before it can be shut down (minimum up-time) or the minimum number of hours a unit must be off-line before it can be brought on-line again (minimum down-time).The minimum up and down times of each unit must be observed.

iv) ***Unit availability constraint-*** This constraint describes whether unit is available / not available, out aged/Must out, Must run, and Fixed Output Power (F.O.P).

The above model outlines the very basic UC problem. Actual systems must consider additional factors, such as ramp rate constraints on thermal units, multi-area UC. The function of UC sometimes includes deciding the practicality of interregional power exchanges and meeting daily or weekly quotas for consumption of fixed batch energies, such as nuclear, restricted natural gas contracts and their fuels that may be in short supply. Moreover, the UC decisions may include use of thermal generating units' alongwith pumped storage capabilities to ensure system reliability using probabilistic measures. The function may also include crew constraints and adequately adopt environmental controls. UC problem is complex to solve due to the presence of binary decision variables on unit status (on/off). This problem essentially belongs to a class of combinatorial optimization problems.

Priority list, augmented Lagrangian relaxation, dynamic programming and the branch-and-bound algorithm are optimization techniques that have been used to solve classic UC problem. Genetic algorithms (GA), simulated annealing (SA), analytic hierarchy process (AHP) and particle swarm optimization (PSO) have also been implemented to UC problem.

2.2 Price Based Unit Commitment

The Generator company (GENCO) in a competitive environment has an objective to produce electricity and sell it with maximum profit. In deregulated power system scenario such type of UC activity can be carried out as if remaining generation is sold in spot market after fulfilling requirements of bilateral transactions. In order to consider effects of contingencies, load variation or spot-market price fluctuations, some amount of reserve generation is ensured at all hours. PBUC's objective is not to meet system load completely but to maximize the profit of GENCO as compared to conventional UC. A typical PBUC model applicable to a GENCO in deregulated environment is described below.

2.2.1 Objective Function of the GENCO

Genco's profit for 24h duration is represented as follows:

Profit = Revenue from [Spot market sell + bilateral power sell]

– Payment for [Spot market buy + unit operating costs +start-up costs + shut-down costs]

Mathematically, this can be expressed

as, $$Profit = \sum_k \left[\begin{array}{c} \rho_{M_k}.PSell_k + BC_k.CP_k - \rho_{M_k}.PBuy_k \\ -\sum_{i=1}^{NG}\{W_{i,k}.CMin_i + PG_{i,k}.GCst_i + UST_{i,k}.ST_i + USD_{i,k}.SD_i\} \end{array} \right]$$

where notation k represents time, ρ_M as the spot-market price, PSell and PBuy as decision variables denoting the amount of power to be traded (sold and purchased, respectively) from the

spot market, BC as the bilaterally contacted power at a price CP. CMin as the generation cost at minimum generation limit of the unit P^{Min}, GCst as the generation cost beyond PMin, ST as the unit start-up cost and SD as the unit shut-down cost. W, UST and USD are binary variables denoting unit status (1=ON, 0=OFF), unit start-up status (1=Start-up, 0=NO) and unit shut-down status (1=Shut-down, 0=NO) respectively.

2.2.2 Constraints

The PBUC is subjected to many constraints that include:

i) Demand-Supply Balance and Spinning Reserves constraint- This constraint is used to meet adequate reserves and bilateral contracted demand requirements by matching generation, spot market purchase by the Genco and the spot market sell after providing for adequate reserves for itself. Therefore, considering simultaneous buying and selling this demand-supply balance condition can be expressed as:

$$W_{i,k}.P_i^{Min} + PG_{i,k} + PBuy_k - PSell_k = BC_k + RESV_k$$

where RESV is the reserve generation capacity that the Genco make available to meet demand changes, or price fluctuations in short term market.

ii) ***Limit on Power Sell-*** Genco's energy transaction commitments must be met in case its bid is selected. Therefore, power selling decision of Genco depends upon its capacity to generate its own by committing its generating units and amount of energy to be bought from spot market.

Apart from above mentioned constraints few more constraints are also used in computing for optimal scheduling such as Ramp rate constraint on thermal units, Minimum up and down-time constraints on thermal units, Maximum and minimum generation limits and Must run units, Sometimes system fuel (fuel type) constraints and system emission constraint are also added for practical purposes. Genco may include its hydro resources also to decide optimal schedule.

2.3 Security Constrained Unit Commitment

The conventional UC algorithm finds thermal units schedule to minimize the operating costs over short-term time span subject to satisfy system constraints such as generation limits, load balance, minimum up/down constraints, system spinning reserve and multiple emission requirements. As the network security constraints are not taken into account, therefore, the conventional UC schedules may fail in practice. SCUC is an important unit commitment formulation not only in regulated power system but also in deregulated power system. The day-ahead schedule is prepared by ISO using SCUC in several power markets [3]. If a large number

of committed generating units belong to one region of power system then it is difficult to satisfy network constraints system wide. Therefore, ISO considers an option to include network flow constraints in UC in order to minimize the violations and other costs for normal operation.

The detailed information of power market such as characteristics of generating units, availability of transmission capacity, generation offers and demand bids, scheduled transactions, curtailment contracts, and so on [4], [5] are utilized in SCUC. The generation dispatch based on SCUC is made available to power market participants (Gencos, Transcos and Discos). The market participants could use the available signals to re-conside their proposed bids on generating resources, which includ signals on LMPs (Locational Marginal Prices) and transmission congestion [6][7][8].

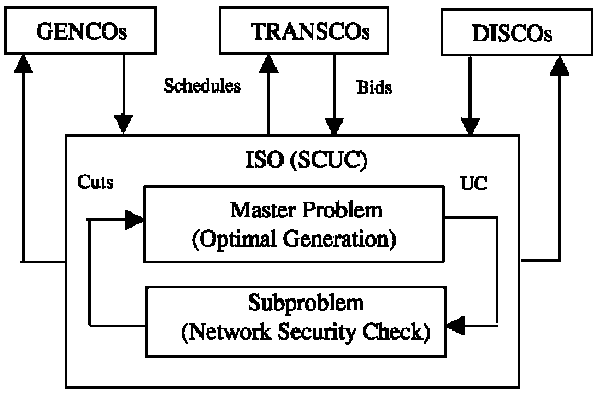

Fig. 2. ISO (SCUC) and main market participants

The complex problem of SCUC is decomposed into two parts namely master problem (UC) and network security check sub problem. The hierarchy to solve SCUC for a restructured power system is shown in Fig. 2. Benders decomposition [9]-[13], decouples the SCUC into a master problem (UC) and a network security check sub problem. In master problem, the available market information is used to calculate UC of generating units. Augmented Lagrangian relaxation (LR) and dynamic programming (DP) methods [109] are used to handle master problem using the prevailing constraints but omitting the network constraints. Subsequently, the constraints are checked by ac network security block on order to minimize network security violations. If violations persist, certain constraints (Benders cuts) will be passed along to the optimal generation block to recalculate the UC solution. All violations are removed by following iterative process and a converged optimal solution is found. The UC problem as a part of SCUC is considered as a large scale nonlinear, non convex and mixed integer problem. Therefore, finding exact optimal solution using computationally inexpensive technique for SCUC is a challenging task.

3. Soft Computing: Hybrid technique for complex problem solving

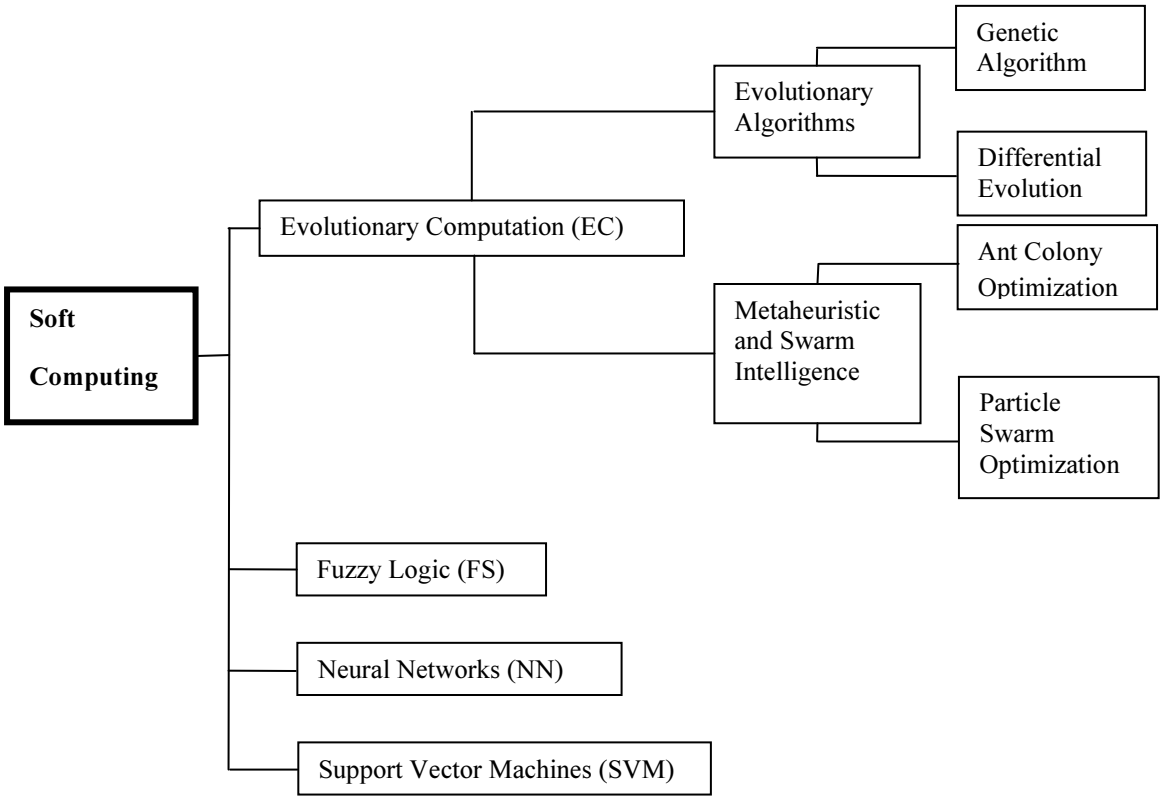

Fig. 3 Different constituents of Soft Computing

The term "Soft computing" is introduced by Prof. Lofti Zadeh with the objective of exploiting the tolerance of imprecision, uncertainty and partial truth to achieve tractability, robustness, low solution cost and better rapport with reality. The ultimate goal is to be able to emulate the human mind as closely as possible. As shown in Fig. 3, soft computing involves partnership of several fields, but essentially not limited to these only. Genetic Algorithms (GAs), Fuzzy logic (FL) and Neural Networks (NN) are important constituents of soft computing. The key features of these techniques along with main applications are highlighted in table 1.

Table 1. Key features of GA, Fuzzy Logic and Neural Networks

GA	Fuzzy Logic	Neural Networks
➢ Adaptive computational procedure based on modeling of natural genetics. ➢ A set of coded solutions are tried at the same time. Moreover, no need to find derivative of the optimizing function. Hence, very little chance to get stuck at local optima when used as optimization technique. ➢ Search space need not be continuous. ➢ Applications in graph coloring, scheduling, numerical optimization, pattern recognition and image processing etc.	➢ An organized method to deal with imprecise data by allowing partial membership rather than crisp set membership or nonmembership. ➢ Processing can be performed even with vague, imprecise, noisy or missing input information. ➢ Multivalued logic allows to apply a more human-like way of thinking in programming of computers. ➢ Problem solving control system methodology which can be implemented ranging from simple, small embedded microcontrollers to large, networked, multichannel PC or workstation-based data acquisition and control systems.	➢ An information-processing model which processes information analogous to human brain. ➢ Remarkable ability to derive meaning from complicated or imprecise data, could be used to extract patterns and detect trends that are complex to be noticed by either humans or other computer techniques. ➢ A trained neural network could be thought as an "expert" in a particular category of information it has been given to analyze. ➢ Applications in deciding strategies for business, games and war, helpful scheduling of buses, airplanes and elevators optimized by predicting demand, pattern recognition, expert consultations etc.

Some of the well popular UC based evolutionary computation methods are differential evolution (DE), genetic algorithm (GA), tabu search, (TS), evolutionary programming (EP), particle swarm optimization, (PSO), ant colony optimization (ACO), harmony search algorithm, (HSA)[112], cuckoo search algorithm (CSA)[113][114][115], immune algorithm (IA). These are based on genetic and evolution mechanisms observed in natural systems and populations of living beings. The meta-heuristic method is an iterative method which not only provides local optimal solution but also gives global or near global optimal solution in most of the times depending on the problem domain and time limit. The recently developed heuristic algorithms, named as Gravitational search algorithm [14] and Quasi-oppositional teaching–learning based optimization (QOTLBO) algorithm [15] are successfully applied to solve UC problem. The field of probabilistic reasoning is also sometimes included under the soft computing umbrella for its control of randomness and uncertainty.

Soft computing is a hybrid technique, which inherits all the advantages, but won't have the less desirable features of single computing component. It has to process an ability to adapt and learn like NN and applicable to complex optimization problems like GA. It should be better than pure GA from learning time point of view and at the same time have low sensitivity to the problem of local minima. Moreover, it may generate a fuzzy knowledge base, which has linguistic representation and a very low degree of computational complexity. The importance of soft computing lies in using these methodologies in partnership. They all offer their own benefits which are generally not competitive and can therefore, work together.

4. Literature Review

4.1 Conventional Unit Commitment

In 2003, Sum and Ongsakul [16] proposed Ant Colony Search Algorithm (ACSA) to solve the thermal unit commitment problem. ACSA is a new cooperative agents approach, which is inspired by the observation of the behaviors of real ant colonies on the topic of ant trial formation and foraging methods. In the ACSA, a set of cooperating agents called "ants" cooperates to find good solution for unit commitment problem of thermal units.

In 2004, Ongsakul and Petcharaks [17] proposed an enhanced adaptive Lagrangian relaxation (ELR) technique for a unit commitment (UC) problem. ELR consists of adaptive LR (ALR) and heuristic search. The ALR algorithm is enhanced by new on/off decision criterion, new initialization of Lagrangian multipliers, unit classification, identical marginal unit de-commitment and adaptive adjustment of Lagrangian multipliers.

In 2006, Kumar and Palanisamy [18] developed a new dynamic programming based on direct computation of Hopfield method for solving short term unit commitment (UC) problems of thermal generators. The proposed two step process uses a direct computation Hopfield neural network to generate economic dispatch (ED). Then using dynamic programming (DP) the generator schedule is produced.

In 2007, Tomonobu et al. [19] proposed an approach, Absolutely Stochastic Simulated Annealing (ASSA) in which probability distributions consumes negligible time with respect to economic load dispatch (ELD) and as a result the reasonable cost improvement is attractive. Finally, the simulation results show a considerable improvement. Juan and Pablo [110], proposed a solution of the short-term hydrothermal generation scheduling problem (HGSP) by using a genetic algorithm and included more capable individuals which was obtained from the hydrothermal coordination stage and it proved to be an effective tool for solving scheduling problems.

In 2008, Titusa & A. Ebenezer [20] worked with EP-PSO-SQP Hybrid Algorithm in which evolutionary programming (EP), particle swarm optimization (PSO), and sequential quadratic programming (SQP) methods are used to solve the dynamic economic dispatch problem (DEDP). Jacob & Prasad [21] made comparison between different real world Unit Commitment Problem Solutions (UCPS) by comparing daily operation planning. The results achieved are encouraging and indicate the viability of proposed technique to deal with future on Unit Commitment Problem (UCP). Patra et al. [22] presented a (DE) Differential Evolution based algorithm for solving Unit Commitment problem with ramp rates constraints. They compared results of the same with other similar methods and shows superiority of the technique.

In 2009, Jeong et al. [23] presented a thermal Unit Commitment Approach through an Improved Quantum Evolutionary Algorithm (IQEA). In this proposed work, UC problems are mathematically formulated as a non-linear, large-scale and mixed-integer combinatorial optimization problem and are solved by applying it on QEA through quantum mechanics.

In 2010, H. Wu et al. [24] worked on Optimal Scheduling with transmission constraints. An effective method is proposed to schedule spinning reserve optimally. The method considers the transmission constraint, forecast uncertainties and the random nature of an outage event. A probabilistic approach is normally used here for solving problems and reserve assessment in the UC function is used which resulting adequate Cost/ Benefit solution of UC problem. Shakarchi and Hassany [25] worked on optimal short-term operation of combinations of UC problems, where the objective function is used to minimize the thermal fuel cost and at the same time it satisfy the hydro and thermal constraints which resulting a system to achieve minimum production cost for the given time period and problem solution of economic operation of hydrothermal power systems. Guang & Chiang [26] produced an effective solution methodology for solving large-scale unit commitment problems using priority list (PL), dynamic programming (DP), the branch-and-bound (B&B) method, the interior point method (IPM), Lagrangian relaxation (LR), the mixed-integer programming (MIP), artificial intelligence (AI) and hybrid approaches resulting an improved solution. Paranjothi & Balaji [27] worked on UCP based Hybrid Genetic Algorithm in which incorporation of Priority List, Dynamic programming, Lagrange Relaxation, Branch-and-Bound, Benders Decomposition, application of Simulated Annealing and Hopfield Neural Networks resulting to determine the alternative to the priority-list method for an initial solution in order to obtain a reduction in the cost of generation.

In 2011, Wang et al. [28] studied about rescheduling of unit commitment problem. In this study, the conventional prediction of future power demands always made based on the historical data. However, the real power demands are affected by many other factors as weather, temperature

and unexpected emergencies. The use of historical information alone cannot well predict real future demands. Jaehyun et al. [29] solved the UC problem through Local Optimal Search Algorithm (LOSA) where the unit commitment problem consists of determining the schedules for power generating units and the generating level of each unit resulting optimal solutions through different solution methods. Rahmani et al. [30] worked on Energy Demand Response Program (EDRP) for solving the UC problem where the Unit Commitment (UC) schedule minimize the system production cost during the given period as well as will satisfy load demands, spinning reserve, ramp constraints, and operational constraints of the given unit or given units of such nature.

In 2013, Jiangtao [31] formulated a scheduling program through Mixed-integer Linear Programming by taking consideration of network programming, dynamic programming, mixed integer programming, genetic algorithm, and Lagrangian relaxation. As result of MILP formulation, a numerical testing is performed for a test example, where the results suggest that the given formulation in this program is efficient and effective sor solving the UC problem. Abaza and Azmy [32] proposed that the dynamic pricing of smart grids based on demand-side management is better than the other pricing methods reported in scheduling.

In 2014, Yuan et al. [33] proposed a scheduling approach with a joint smart generation by including some of the part of electrical energy from wind forms and converting it into different forms of energy for storage, Different optimization approaches considering the requirements of storage capacity were applied to the operation of a wind–hydro pumping storage power system, resulting more sustain results then early approaches of scheduling. Yurong et al. [34] proposed UC problem solution with uncertainty in presence of wind power which also results in uncertain output range. They used fuzzy modeling for Economic Load Dispatch (ELD) & Dynamic Economic Dispatch (DED) models which subsequently integrated to get optimal results. Xiang & Zhang [35] proposed Lagrangian relaxation and particle swarm optimization method for solving Unit commitment problem which shows that improved UC schedule may significantly save the power generation cost by millions of revenue per year through various hybrid optimization algorithms. Roy & Sarkar [36] provided another quasi-oppositional teaching learning based algorithm for unit commitment problem in which forecasted demand and other system operating constraints are used to get adequate results over demand and spinning reserve capacity of the operating units within each specific time of operation. Zeng et al. [37] prepared a solution of UCP and studied about wind power and pumped hydro energy storage which found most cost-optimal units and maintained on-line status in the dispatching cycle.

4.2 Price based Unit Commitment

In 2002, Attaviriyanupap et al. [38] presented a new profit-based UC problem in restructured power system. The proposed algorithm finds the most economical scheduling plan for generation companies (GENCO) by considering both power and reserve generation. Price based Unit Commitment (PBUC) problem is solved under comparative environment to minimize total production cost as well as constraints are satisfied such as power demand, spinning reserve so that the minimum up and down times can be met within most economic way.

In 2003, Attaviriyanupap et al. [39] proposed another hybrid LR-EP UC problem under competitive environment and provides some better reserve payment methods rather than traditional UC methods by enchanting costumes with the help of Lagrange Relaxation (LR) method which seems to be the most suitable over some other like stochastic optimizations, genetic algorithm (GA) and evolutionary programming (EP) etc.

In 2004, Jing et al. [40] presented a solution of PBUCP using Multi-Agent System in which the result is only near optimal, but the system can solve the great number of uncertainties of unit commitment problem in the business environment of deregulated power systems in a distributed way.

In 2005, Pereira et al. [41] suggested PBUC by cold reserve under competitive environment and provided that the cold reserve would be of great importance for a system, where the majority of the generating units are located far away from the consumers, because they, if placed in the vicinity of large consumer centers, can be turn-on in case of loss of transmission lines, power substations or rationing energy.

In 2006, Ghose et al. [42] presented an augmented pricing approach along with genetic algorithm based unit commitment to attain market equilibrium at such periods. In this paper author uses a different technique to get the optimal level of power generation on forecasted spot price as part of unit commitment. Test results justify the effectiveness of the technique along with the proposed modifications.

In 2007 Sen & Kothari [43] worked on a UC approach deals with quantification of the benefit of interconnection between two large areas having different Load -Generation characteristics. A multi-area unit commitment model based on Capacity Utilization Factor(CUF) and sequential techniques including DC(direct current) power flow module is developed to estimate the constrained both (system and transmission) inter-area energy exchange and its associated production cost. Feng & Laio [44] presented a solution of Unit Commitment problem based on Lagrangian Relaxation in multiplier update approach in deregulated environment. In this article author presents an improved subgradient based method on the concept of step size scaling factor

that may achieve speedy convergence for dual optimization. In this method local and global constraints, reserve requirements and energy balance constraints are used for specified control areas and regions for the entire system. Results demonstrated the effectiveness of the proposed approach.

In 2008, Chandram et al. [45] worked to solve PBUC problem through Muller method by improved pre-prepared power demand table in which problem is solved in two stages and it is observed from the simulation results that the proposed algorithm provides maximum profit with less computational time.

In 2009, Mori and Okawa [46] proposed a meta-heuristic method under competitive environment for PBUCP. In this method the nonlinear mixed-integer problem of the PBUC divides into two layers and method succeeded in increasing about 17.5% of the profits for traditional UC through incorporating minimizing operation cost of units by satisfying the constraints and characteristics. Raglend et al. [51] solved the profit based unit commitment problem under deregulated environment, resulting most economical scheduling plan for GENCO by considering both power and reserve generation for solving the schedule of generating units within a power system with different number of constraints. Karki & Billinton [47] analyzed multi stage generating unit modal utilization in unit commitment problem in which unit failure rate data in the IEEE-RTS was replaced by actual data and resulting more accurate representation of the performance of a generating unit. Therefore, a more accurate assessment of the UCP with incorporation of multi-state generating unit models is achieved in conventional practice.

In 2010, Yamin & Shahidehpour [48] worked on bidding strategies of PBUC in deregulated market by incorporation of system spinning reserve, ramp rate limits, fuel constraints, multiple emission requirements as well as minimum up and down time limits over a set of time periods.

In 2011 Sharma et al. [49] also used multi-agent approach but in terms of price based UC in deregulated market by approaching profit based UC (PBUC). In this method hard constraints on demand and reserve are modeled as inequality constraints and solved the problem through priority list and dynamic programming. However, this method is not suitable for large systems. Therefore, the author proposes a combinations of Lagrange relaxation (LR), branch-and-bound method and muller based method for better results.

In 2012, Selvakuma et al. [50] presented a solution for PBUC problem by Shuffled Frog Leaping Algorithm. In this algorithm generation schedule is independently solved with minimum operating cost and satisfying the demand and reserve requirements and the results are quite impressive.

In 2013, Derakhshandeh et al. [52] worked on fair allocation of cost saving with respect to security constraints of profit-based unit commitment by using distribution network. It is seen that it can operate in both grid-connected and stand-alone modes, and provide maximizing security and minimizing cost to increase the total profit and decrease the overall cost of Industrial Micro-Grids (IMGs).

In 2014, Ping & Gang [53] worked with emissions penalty for Profit-Based Unit Commitment problem by a Mixed-Integer Linear Programming (MILP). The outcomes of MILP approach can find the optimal solution in a reasonable time and emission reduction policy in the deregulated electricity market. Govardhan et al. [54] used global best artificial bee colony algorithm (GABC) and teaching-learing based optimization (TLBO) for solving Price Base Unit Commitment problem with the compulsion of satisfying the end user's load demand and the results obtained by GABC, TLBO are compared. In this comparison it is found that the results through TLBO are superior than GABC and NACO.

4.3 Security – Constrained Unit Commitment

In 2002, Yamin, H.Y. [55] described about a coordination process between GENCOs and the ISO for congestion management and reducing the risk of failure to supply loads by including generation and adjustment bids, security constrained price based unit commitment (SPUC) decomposes the problem into a master problem (GENCOs) and in a sub problem (BO) based on Benders decomposition

In 2005, Yong et al. [56] propose that the independent system operator (ISO) can executes the security-constrained unit commitment (SCUC) program to plan a secure and economical hourly generation schedule for the day-ahead market and introduces an efficient SCUC approach with AC constraints which resulting the minimum system operating cost while maintaining the security of power systems. Bo Lu & Shahidehpour [57] propose that the competitive generation units must have the ability for operating under flexible conditions to respond to various market driving forces. Among generating units with flexible operating conditions, those with fuel switching and fuel-blending capabilities, as well as combined cycle units, are commonly considered for responding to volatile market environments including standard market design (SMD). Zuyi & Shahidehpour [58] introduced a security-constrained unit commitment (SCUC) model with emphasis on the simultaneous optimization of energy and ancillary services markets. Benders decomposition is used to decouple the SCUC into a unit commitment master problem and hourly network security checking subproblems. Lagrangian relaxation is used to decouple the UC problem into individual single-unit commitment problems resulting optimality of conditions for calculating energy and ancillary services are discussed in detail. Xiaohong et al. [59] proposed to obtain feasible solutions by adjusting generation levels with the

commitment states obtained in the dual solution of Lagrangian relaxation. The analytical and computational necessary and sufficient conditions are presented to determine the feasible unit commitment states with grid security constraints.

In 2006, Mitani et al. [60] proposes a new solution algorithm of the security constrained unit commitment based on Lagrangian decomposition and tabu search. By the Lagrangian decomposition, the problem can be divided into two sub problems the unit commitment problem of the time zones and the optimal operation problem of each generator. Collett, & Quaicoe [61] investigated a novel approach for solving security-constrained unit commitment (SCUC) problems. These problems involve the development of generation schemes for a power system while adhering to a set of operational constraints. Yong et al. [62] proposed an effective AC corrective/preventive contingency dispatch over a 24-h period based on security-constrained unit commitment (SCUC) model. The SCUC model includes unit commitment, AC security-constrained optimal power flow (SCOPF), load shedding (LS) for steady state and contingencies. Chhetri et al. [111] presented a method for minimizing the energy supply cost of an electricity market with multiple regions interconnected by tie lines. It optimally commits the least number of generating units through a Security Constrained Unit Commitment procedure.

In 2007, Lei et al. [63] presented a stochastic model for long-term solution of security-constrained unit commitment (SCUC). The proposed approach could be used by vertically integrated utilities as well as the ISOs in electricity markets. In this model, random disturbances, such as outages of generation units and transmission lines as well as load forecasting inaccuracies, are modeled.

In 2008 Zhaoqiang & Cao [64] proposed a mathematical model to solve security constrained unit commitment problem (SCUCP), where the security constrained economic dispatch executed by dispatch center will guarantee that unit schedule should satisfy minimum security level. In this model unit commitments submitted by provincial dispatch center are also made out by experience. During the simulation and trial run, the security-constrained economic dispatch (SCED) was used to find the cost-effective generation schedule in this area.

In 2009, Askarpour and Zeinadini [65] proposed to solve UC problem by predicting the market behavior using the historical prices, loads and other required information to forecast the future prices and loads. In this regard, forecasting of the loads and prices are made by artificial neural networks (ANN) and IEEE 30 bus test system is used for the ANN results. Yong et al. [66] proposed a model to solve the coordinated generation and transmission maintenance scheduling with security-constrained unit commitment (SCUC) over the scheduling horizon of weeks to months. The model applies the Lagrangian relaxation technique to decompose the optimization

problem into sub-problems for generation maintenance scheduling, transmission maintenance scheduling and short-term SCUC.

In 2010, Bozorg et al. [67] proposed a method for solving UC problem by providing the customer to choose tradeoff between cost and reliability level that suits them, which is one of the most important targets of restructured power system. In this regard the centralized management of reliability in vertically integrated utility (VIU) will also apply the same policies to different customers which will replace the decentralized management and allowing customers to participate in reliability management based UC on their required reliability levels. Kumar & Mohan [68] proposed Optimal Power Flow (OPF) with line flow constraints to solve the Unit Commitment (UC) problem using Genetic Algorithm (GA). In this approach the problem is solved in two phases. In the first phase, unit commitment is solved with prevailing constraints, without line flow constraint by genetic algorithm. In the second phase, the violations in the lines are minimized for a committed schedule using GA based OPF. The resulting solution minimizes line flow violations in the critical lines under unit's de-committed hours by adjusting the unit generations. Qiaozhu et al. [69] propose a method to identify the feasibility of the unit commitment state and security constraints is crucial for solving SCUC problems. It is found that if the feasibility of unit commitment state can be identified quickly without more computational time then the efficiency of SCUC problem-solving methods can be greatly improved in all manners. Chakraborty et al. [70] presented an approach to determine the security constrained unit commitment (SCUC) for thermal units integrated with wind power system. A Lagrangian relaxation based algorithm with Particle Swarm Optimization (PSO) has been applied to solve this model. Lotfjou et al. [71] presented the solution to the security-constrained unit commitment (SCUC) problem with a detailed representation of high voltage direct current (DC) transmission system with current source converters (CSCs). The SCUC problem is decomposed into a master problem for solving unit commitment (UC) problem and hourly transmission security check sub-problems that evaluate branch flows and bus voltages of integrated AC/DC transmission systems. Khodaei and Shahidehpour [72], proposed a solution for transmission switching (TS) to find the optimal dispatch of units when considering network constraints. The TS sub-problem also examines contingencies and identifies required changes to the UC master problem solution when contingencies cannot be mitigated in the TS sub-problem and provided solution in which TS was integrated with UC for solving the multi-interval optimal generation unit scheduling with security constraints. Laothumyingyong and Damrongkulkamjorn [73] proposed a method to determine the 24-hour unit commitment with minimum total generation cost subjected to power flow constraints in both normal operating state and contingency state. Qiaozhu et al. [74] proposed a method to establish to satisfy security constraints and difficult constraints for unit commitment problems. If the inactive

security constraints can be identified and eliminated, the SCUC problem can be greatly simplified. In this method, a necessary and sufficient condition for a security constraint to be inactive is established.

In 2011, Nima et al. [75] proposed a new formulation of Security Constrained Unit Commitment (SCUC) problem, considering more practical constraints and nonlinear characteristics than previous works in the area. The proposed SCUC formulation includes Prohibited Operating Zones (POZs), valve-loading effects, and multiple fuel options of generating units.

In 2012, Lyua et al. [76] proposed a new and efficient approach to determine security-constrained generation scheduling (SCGS) in large-scale power systems, taking into account dispatch, network, and security constraints in pre and post-contingency states. A novel ramp rate limit is also modeled as a piecewise linear function in the SCGS problem to reflect more practical characteristics of the generating units. Nima & Ansari [77] proposed a new hybrid solution approach based on Benders decomposition and outer approximation to solve the security-constrained unit commit- ment problem. The security-constrained unit commitment model includes both thermal and hydro unit commitment as well as AC network modeling. The proposed solution method decomposes the security-constrained unit commitment formulation into a master problem and sub-problem. Simon & Columbus [78] developed scheduling algorithm using hybrid particle swarm optimization (PSO) for electric generation that accounts directly for system security requirements. The proposed SCUC formulation includes constraints, such as hourly power demand, system reserves, ramp up/down limits, minimum ON/OFF duration limits.

In 2013, Papavasiliou & Oren [79] developed systematic methods for committing locational reserves in order to secure the system against contingencies, while accounting for power flow constraints imposed by the transmission network and the results are quite impressive. Alemany et al. [80] proposed a method to accelerate the Benders classic algorithm for emphasizing their application to solve the problem of SCUC by involving pre-dispatching resolution of complex problems. Yong et al. [81] proposed a method to evaluate capabilities and performances of some algorithm of SCUC through numerical testing where special large-scale SCUC engine development are also included. Some approaches are used like input data screening, inactive constrains elimination, contingency management, infeasibility handling, parallel computing, and model simplification, resulting less computational time with comparison to other constrains satisfaction. Karami et al. [82] presented the application of Mixed-Integer Programming (MIP) approach for solving the security-constrained daily hydrothermal generation Scheduling which takes into account the intermittency and volatility of wind power generation, which is called

security-constrained Wind Hydro Thermal Coordination (WHTC). Mahdi et al [83] proposed a new combinatorial solution strategy for security constrained unit commitment (SCUC) problem. In the proposed combinatorial solution strategy, the unit states are determined by a new stochastic search method, which is an enhanced harmony search technique, and the security constrained economic dispatch problem is solved using an efficient nonlinear analytical solver based on numerical optimization. Bertsimas et al. [84] proposed a two-stage adaptive robust unit commitment model for the security constrained unit commitment problem in the presence of nodal net injection uncertainty. Compared to the conventional stochastic programming approach, the proposed model is more practical as it only requires a deterministic uncertainty set rather than a hard-to-obtain probability distribution on the uncertain data.

In 2014, Mollahassani et al. [85] suggested, a new structure for security-constrained power management system (PMS) associated with demand response (DR) programs. In order to scrutinize the economic and environmental driven measures of DR programs, a new linearized formulation of cost and emission based preventive maintenance problem is presented. Kargarian et al. [86] proposed the centralized SCUC algorithm which could face critical challenges ranging from modeling accuracy to calculation complexity. This work presents a distributed SCUC (D-SCUC) algorithm to accelerate the generation scheduling of large-scale power systems. Bigdeli & Karimpour [87] presented Security Constraint Unit Commitment (SCUC) backup plan considering single contingency. The proposed method leads solution to obtain optimal units and reserve schedule. In equivalent linear expression of the problem, shedding costs are used to avoid divergence and resolve congestion problem. Chen and Li [88] proposed a method in which a combined model of optimal reserve dispatch and security-constrained unit commitment (SCUC) considering uncertain wind energy generation output is presented. To simulate the volatility and intermittency of wind energy, scenarios are generated by using Monte Carlo simulation with Latin hypercube sampling technique. Mohammad et al. [89] proposed a method for short term security-constrained unit commitment (SCUC) for hydro and thermal generation units. The SCUC problem is modeled as a multi-objective problem to concurrently minimize the ISO's cost as well as minimize the emissions caused by thermal units. The non-linearity of valve loading effects is linearized in the presented problem. Azza A. ElDesouky [90] proposed a security constrained generation scheduling (SCGS) problem for a grid incorporating thermal, wind and photovoltaic (PV) units. The formulation takes into account the stochastic nature of both wind and PV power output and imbalance charges due to mismatch between the actual and scheduled wind and PV power outputs. Mir et al. [91] designed a Demand Response Programs (DRPs) to consider the consumers participation. One of these programs named as Emergency Demand Response Program (EDRP) is based on consumers' responses to high electricity prices and to the incentives that are paid by

Independent System Operators (ISOs) in the critical hours. Ming et al. [92] proposed a interval optimization combined with point estimation (IO-PEM) method to solve the stochastic nature of unit commitment problem induced by wind power fluctuation. Considering reasonable fluctuation range of wind power, an interval optimization model is established which takes two worst-case scenarios to replace all scenarios in the interval. This model accelerates the solution speed on the premise that the scheduling result meets security constraints. At the same time, in order to accurately evaluate corrective dispatching cost caused by wind power fluctuations and make the scheduling scheme more economic.

In 2015, Ehsan & Hassan [93] proposed and demonstrated that spinning reserve allocation should be done such that transmission system limits are accommodated if the spinning reserve resources are activated. It has been observed that in some cases, spinning reserve can-not be activated by the system operator to respond to deviations from the wind power forecast values due to encountering congestion in the transmission system. Alemany and Magnago [94] proposed a new Benders Decomposition (BD) initialization methodology applied to SCUC problems. The initialization was based on the addition of inexpensive cuts to the initial UC master problem. The initial cuts were obtained after the application of the following steps: calculation of Load Supplying Capability (LSC), calculation of mixed integer leaner (MIL), calculation of relaxed horizon UC, elimination of redundant network constraints, calculation of Linear Load Flow (LLF) with rescheduling, and upgrading of Benders cuts. Sreejith et al. [95] focused on solving Security Constrained Unit Commitment (SCUC) problem using Artificial Bee Colony (ABC) algorithm incorporating FACTS devices. The objective of the SCUC problem is to obtain the minimum operating cost simultaneously maintaining the security of the system.

5. Research Motivation

In recent times, the UC is not only important from power system economy point of view but of great significance due to following reasons.

- The variation between peak and off-peak power demands is increased a lot.
- The restarting of modern generating facilities are much complex due to start-up, shut-down and dynamic considerations in comparison to smaller older units.
- Even small percentage gains seem to be economically important due to continuous growth in power system size.
- Automated computerized schedulers are required by power system planners to simulate the effect of unit selection methods on the choice of new generation.

The UC problem has grown out of the effective reach of the “earlier” techniques because of the large variety of efficiencies and types of power sources. In the past, deterministic techniques such as branch and bound method (BABM) [96], dynamic programming (DP) [97], priority list method (PLM) and lagrangian relaxation method (LRM) [98][99] are applied to solve this problem. Although PLM, DP and LRM techniques are mostly used but suffer form a drawback of being more computational and expensive as the optimization problem grown in both dimensionality and complexity [100]. The development of various soft computing techniques by various researchers during last 10-15 years made possible advancement in computation and the searching for better results for complex optimization problems. The random search techniques like genetic algorithm (GA) [101], particle swarm optimization (PSO) [102], simulated annealing (SA) [103], Tabu search [104], analytic hierarchy process (AHP) [105], evolutionary programming (EP) [106] and ant colony search method (ACSM) [16] are applied to conventional UC problem. Fuzzy logic and Artificial Neural Networks (ANN) are also applied in this context. The further improvement in the results of such a complex optimization problem can be expected by hybridization of soft computing constituents.

In PBUC, generator units ON/OFF status are decided by energy market price signal. The problem become difficult to solve when fuel price is not constant and depends on total MBtu consumption [4]. Depending upon ramp rates the generation unit scheduling and profit also change. The PBUC formulation can simulate transmission congestion by considering price difference among different regions i.e. through different locational marginal prices (LMPs). The above mentioned factors demand an efficient solution methodology for the PBUC problem in a deregulated power system which allows Gencos to commit and schedule their units for selling power, purchasing power, selling spinning and non-spinning reserves in order to maximize their profits. The performance of artificial intelligence based optimization techniques are better than any classical method such as LRM as clear from the literature survey in previous section. Therefore, there is a need to develop more efficient soft computing based optimization techniques in this regard.

SCUC is another complex optimization problem due to time-varying, non-linear, non convex and mixed integer nature. In conventional LR approach, the Lagrangian dual function is formed by adjoining a set of coupling constraints to the UC primal objective function via Lagrange multipliers. The dual problem is decoupled into unit based sub problems which are easier to solve. The difficulties were reported in obtaining a feasible solution due to the non-convexity of the resource scheduling problems [107]. A linear programming methodology is also used to solve SCUC problem with an extended DC network model [108]. Since the conventional techniques are unable to provide adequate results, therefore effectiveness of hybrid soft computing techniques can be tested for this problem.

6. Research Objectives

The new soft computing techniques will be developed in proposed research work and implemented to selected unit commitment models such as Conventional UC in regulated power system, PBUC and SCUC in deregulated power system scenario. In this research work, it is proposed to undertake the following:

- To study in detail, existing artificial intelligence (AI) and soft computing techniques with reference to develop optimization technique while handling complexities of unit commitment models.
- To develop soft computing based optimization techniques, their verification and validation of developed techniques using benchmark testing problems.
- Application of proposed soft computing techniques for the following power system optimization problems:
    a) In conventional unit commitment, to deal complex issues such as easy minimum up and down time constraint handling, consideration of convex and non convex cost function and low total production cost etc. Also, the performance of proposed methodology to be compared with existing methods for the same conventional UC model.
    b) In Price based Unit Commitment (PBUC) and Security constrained Unit Commitment (SCUC) models for deregulated power system and analyze its performance by comparing performance of other existing methods.

7. References

[1] Kerr. R.H., Scheidt, J.L, Fontana. A.J and Wiley. J.K, Unit commitment, IEEE transactions on power systems, vol. 85, No. 5, pp. 417-421, May 1966.

[2] Wood. A.J and Wollenberg. B.R, Power generation operation and control, Wiley and sons Inc., Delhi, 2006.

[3] Amjady, Nima & Ansari, Mohd. Reza, "Security-constrained Unit Commitment considering Hydro Units and AC Network Modeling by a New Hybrid Solution Method composed of Benders Decomposition and Outer Approximation", Electric Power Components and Systems, Vol. 40, No. 13, pp. 1445-1469, 2012.

[4] M. Shahidehpour, H. Yamin and Z. Li, "Market Operations in Electric Power Systems: Forecasting, Scheduling and Risk Management", IEEE Intersience, John Wiley & Sons Publishers, 2002.

[5] M. Shahidehpour and M. Marwali, Maintenance Scheduling in Restructured Power Systems. Norwell, MA: Kluwer, 2000.

[6] S. Wang, M. Shahidehpour, D. Kirschen, S. Mokhtari, and G. Irisarri, "Short-term generation scheduling with transmission and environmental constraints using an augmented Lagrangian relaxation," IEEE Trans. Power Syst., vol. 10, no. 3, pp. 1294–1301, Aug. 1995.

[7] K. Abdul-Rahman, M. Shahidehpour, M. Aganagic, and S. Mokhtari, "A practical resource scheduling with OPF constraints," IEEE Trans. Power Syst., vol. 11, no. 1, pp. 254–259, Feb. 1996.

[8] C. Wang and M. Shahidehpour, "Ramp-rate limits in unit commitment and economic dispatch incorporating rotor fatigue effect," IEEE Trans. Power Syst., vol. 9, no. 3, pp. 1539–1545, Aug. 1994.

[9] N. Deeb and M. Shahidehpour, "A decomposition approach for minimizing real power losses in power systems," Proc. Inst. Elect. Eng. C, vol. 138, no. 1, pp. 27–38, Jan. 1991.

[10] N. Deeb and M. Shahidehpour, "Cross decomposition for multi-area optimal reactive power planning," IEEE Trans. Power Syst., vol. 8, no. 3, pp. 1539–1544, Nov. 1993.

[11] M. Shahidehpour and V. Ramesh, "Nonlinear programming algorithms and decomposition strategies for OPF," in IEEE/PES Tutorial on Optimal Power Flow. Piscataway, NJ: IEEE Press, 1996.

[12] N. Alguacil and A. Conejo, "Multiperiod optimal power flow using benders decomposition," IEEE Trans. Power Syst., vol. 15, no. 1, pp. 196–201, Feb. 2000.

[13] A. M. Geoffrion, "Generalized benders decomposition," J. Optim. Theory Appl., vol. 10, no. 4, pp. 237–261, 1972.

[14] Provas Kumar Roy, " Solution of unit commitment problem using gravitational search algorithm", Electrical Power and Energy Systems 53, pp. 85–94, 2013.

[15] Provas Kumar Roy and Ranadhir Sarkar, "Solution of unit commitment problem using quasi-oppositional teaching learning based algorithm", Electrical Power and Energy Systems 60, pp. 96–106, 2014.

[16] Sum-Im, T. ; Ongsakul, W., "Ant colony search algorithm for unit commitment" Industrial Technology, 2003 IEEE International Conference on Volume: 1, Page(s): 72 – 77, 2003.

[17] Ongsakul, W. ; Petcharaks, N., "Unit commitment by enhanced adaptive Lagrangian relaxation" Power Systems, IEEE Transactions on Volume: 19 , Issue: 1, Page(s): 620 – 628, 2004.

[18] Kumar, S.S. ; Palanisamy, V., "A New Dynamic Programming Based Hopfield Neural Network to Unit Commitment and Economic Dispatch" Industrial Technology, 2006. ICIT 2006. IEEE International Conference, Page(s): 887 – 892, 2006.

[19] Tomonobu Senjyu, Ahmed Yousuf Saber, Tsukasa Miyagi, Naomitsu Urasaki & Toshihisa Funabashi "Absolutely Stochastic Simulated Annealing Approach to Large Scale Unit Commitment Problem", University of the Ryukyus , Okinawa, Japan Meidensha Corporation, Tokyo, Japan, Taylor & Francis, 2007.

[20] S. Titusa & A. Ebenezer Jeyakumarb "A Hybrid EP-PSO-SQP Algorithm for Dynamic Dispatch Considering Prohibited Operating Zones" Department of Electrical and Electronics Engineering, pages 449-467, Taylor & Francis, Apr 2008.

[21] I. Jacob Raglend & Narayana Prasad Padhy "Comparison of Practical Unit Commitment Problem Solutions", Electric Power Components and Systems, 36:8, 844-863, Taylor & Francis, 2008.

[22] S. Patra , S. K. Goswami & B. Goswami Differential Evolution Algorithm for Solving Unit Commitment with Ramp Constraints, Electric Power Components and Systems, 36:8, 771-787, Taylor & Francis, 2008.

[23] Yun-won Jeong, Jong-bae Park, Joong-rin Shin and Kwang y. Lee "A Thermal Unit Commitment Approach Using an Improved Quantum Evolutionary Algorithm", Department of Electrical Engineering, Konkuk University, Seoul, Korea and Department of Electrical and Computer Engineering, Baylor University, Waco, Texas, USA, pages 770 – 786, Taylor & Francis, 2009.

[24] H. Wu, H. B. Gooi, C. Y. Teo, "Optimal Scheduling of Spinning Reserve with Transmission Constraints" School of Electrical and Electronic Engineering Nanyang Technological University Nanyang Avenue, Singapore 639798, Taylor & Francis, Nov 2010.

[25] M. R. G. Al-Shakarchi, H. D. H. Al-Hassany, "Short-Term Hydrothermal Power System Unit Commitment: A Comparative Study" College of Engineering Ajman University of Science and Technology United Arab Emirates, Previously at the Electrical Engineering Department University of Technology Baghdad, Iraq, Taylor & Francis, Nov 2010.

[26] Yu-Guang Xie & Hsiao-Dong Chiang, "A Novel Solution Methodology for Solving Large-scale Thermal Unit Commitment Problems", Department of Electrical Engineering, School of Electronic, Information and Electrical Engineering, Shanghai Jiaotong University , Shanghai, China, School of Electrical and Computer Engineering, Cornell University , Ithaca, New York, USA, Taylor & Francis, Dec 2010.

[27] S. R. Paranjothi & V. Balaj, "Hybrid Genetic Algorithm- Based Unit Commitment", Electric Power Components and Systems, Taylor & Francis, 1047-1054 Nov 2010.

[28] Bo Wang ; You Li ; Watada, J. "Re-scheduling the unit commitment problem in fuzzy environment" Fuzzy Systems (FUZZ), 2011 IEEE International Conference, Page(s): 1090 – 1095, 2011.

[29] Jaehyun Bae ; Sangheon Jeong ; Youngmin Kim ; Heesang Lee "Local optimal search algorithm for unit commitment problem", Advanced Power System Automation and Protection (APAP), 2011 International Conference on Volume: 2, Page(s): 1317 – 1323, 2011.

[30] Rahmani – Andebili, M. ; Abdollahi, A. ; Moghaddam, M.P. “An investigation of implementing Emergency Demand Response Program (EDRP) in Unit Commitment problem”, Power and Energy Society General Meeting, 2011 IEEE, Page(s): 1 – 7, 2011.

[31] Jiangtao Jia “Mixed-integer Linear Programming Formulation for Short-term scheduling of Cascaded Hydroelectric Plants with Pumped-storage Units”, Electric Power Components and Systems, 41:15, pages 1456 -1468, Taylor & Francis, 2013.

[32] Abaza, A. ; Azmy, A.M. “Demand-side management-based dynamic pricing within smart grid environment”, Smart Energy Grid Engineering (SEGE), 2013 IEEE International Conference, Page(s): 1 – 6, 2013.

[33] Bo Yuan , Ming Zhou , Xiao-ping Zhang & Gengyin Li “A Joint Smart Generation Scheduling Approach for Wind Thermal Pumped Storage Systems”, Electric Power Components and Systems, 42:3-4, 372-385, Taylor & Francis, 2014.

[34] Yurong Zhang ; Bin Wang ; Min Zhang ; Yi Feng ; Wenzhong Cao ; Lin Zhang, “Unit commitment considering effect of load and wind power uncertainty” Advanced Research and Technology in Industry Applications (WARTIA), IEEE Workshop, Page(s): 1324 – 1328, 2014, 2014.

[35] Xiang Yu, Xueqing Zhang, “Unit commitment using Lagrangian relaxation and particle swarm optimization”, Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, Electrical Power and Energy Systems 61, 510–522, ELSEVIER, 2014.

[36] Provas Kumar Roy, Ranadhir Sarkar, “Solution of unit commitment problem using quasi-oppositional teaching learning based algorithm”, Department of Electrical Engineering, Dr. B C Roy Engineering College, Durgapur, West Bengal, India, Electrical Power and Energy Systems 60, 96–106, ELSEVIER, 2014.

[37] Zeng Ming, Zhang Kun, Wang Liang, “Study on unit commitment problem considering wind power and pumped hydro energy storage”, School of Economics and Management, North China Electric Power University, Beijing 102206, China, Electrical Power and Energy Systems 63, 91–96, ELSEVIER, 2014.

[38] Attaviriyanupap, P., Kita, H., Tanaka, E., Hasegawa, J., “A new profit-based unit commitment considering power and reserve generating”, Power Engineering Society Winter Meeting, 2002. IEEE Volume: 2, Page(s): 1311 – 1316, 2002.

[39] Attaviriyanupap, P. ; Kita, H. ; Tanaka, E. ; Hasegawa, J., “A Hybrid LR-EP for Solving New Profit-Based UC Problem under Competitive Environment”, Power Engineering Review, IEEE Volume: 22 , Issue: 12, Page(s): 62 and 229 – 237, 2003.

[40] Jing Yu ; Jianzhong Zhou ; Wei Wu ; Junjie Yang ; Wei Yu, “Solution of the profit-based unit commitment problem by using multi-agent system”, Intelligent Control and Automation, 2004. WCICA 2004. Fifth World Congress on Volume: 6, Page(s): 5079 – 5083, 2004.

[41] Pereira-Neto, A. ; Saavedra, O.R. ; Unsihuay, C. ; Pessanha, J.O., "Profit based unit commitment considering the cold reserve under competitive environment", Power Tech, 2005 IEEE Russia, Page(s): 1 – 4, 2005.

[42] Ghose, T. ; Gopi Kishore, M. ; Sukumar, P. "Solution of profit based unit commitment considering market equilibrium condition", Power India Conference, 2006 IEEE, 2006.

[43] Subir Sen & D. P. Kothari "evaluation of benefit of inter-area energy exchange of the indian power system based on multi-area unit commitment approach, Electric Machines & Power Systems, 26:8, 801-813, Taylor & Francis, 2007.

[44] Xiaoming Feng & Yuan Liao "A New Lagrangian Multiplier Update Approach for Lagrangian Relaxation Based Unit Commitment", Electric Power Components and Systems, 34:8, 857-866, Taylor & Francis, 2007.

[45] Chandram, K. ; Subrahmanyam, N. ; Sydulu, M., "Improved pre-prepared power demand table with Muller method for solving Profit Based Unit Commitment", TENCON 2008 - 2008 IEEE Region 10 Conference, Page(s): 1 – 6, 2008.

[46] Mori, H. ; Okawa, K., "A new meta-heuristic method for profit-based unit commitment under competitive environment", PowerTech, 2009 IEEE Bucharest, Page(s): 1 – 6, 2009.

[47] Bipul Karki & Roy Billinton "Utilization of Multi-state Generating Unit Models in Unit Commitment Risk Analysis of Wind-integrated Power Systems", Electric Power Components and Systems, 37:10, 1118-1132, Taylor & Francis, 2010.

[48] H. Y. Yamin & S. M. Shahidehpour, Bidding Strategies Using Price Based Unit Commitment in a Deregulated Power Market, Electric Power Components and Systems, Taylor & Francis, 32:3, 229-245, 2010.

[49] Sharma, D. ; Srinivasan, D. ; Trivedi, A., "Multi-agent approach for profit based unit commitment", Evolutionary Computation (CEC), 2011 IEEE Congress, Page(s): 2527 – 2533, 2011.

[50] Selvakumar, K. ; Venkatesan, T. ; Sanavullah, M.Y., "Price Based Unit Commitment Problem Solution using Shuffled Frog Leaping Algorithm", Advances in Engineering, Science and Management (ICAESM), IEEE 2012 International Conference, Page(s): 794 – 799, 2012.

[51] Raglend, I.J. ; Kumar, R. ; Karthikeyan, S.P. ; Palanisamy, K. ; Kothari, D.P., "Profit based unit commitment problem under deregulated environment", Power Engineering Conference, 2009, AUPEC 2009, IEEE, Australasian Universities, Page(s): 1 – 6, 2009.

[52] Derakhshandeh, S.Y. ; Golshan, M.E.H. ; Masoum, M.A.S., "Profit-based unit commitment with security constraints and fair allocation of cost saving in industrial microgrids" Science, Measurement & Technology, IET Volume: 7 , Issue: 6, Page(s): 315 – 325, 2013.

[53] Ping Che ; Gang Shi, "An MILP approach for a profit-based unit commitment problem with emissions penalty", Control and Decision Conference (2014 CCDC), IEEE 2014, Page(s): 4474 – 4477, 2014.

[54] Govardhan, M. ; Mishra, M. ; Sundeep, S. ; Roy, R., “Solution of price based unit commitment using GABC and TLBO optimization algorithms”, Control, Instrumentation, Energy and Communication (CIEC), IEEE, 2014 International Conference, Page(s): 667 – 671, 2014.

[55] Yamin H.Y. “Security-constrained price-based unit commitment in the deregulated power market” Power Engineering 2002, Large Engineering Systems Conference, Page(s): 18 – 22, 2002.

[56] Yong Fu ; Shahidehpour, M. ; Zuyi Li “Security-Constrained Unit Commitment With AC Constraints Power Systems”, IEEE Transactions on Volume: 20 , Issue: 3, Page(s): 1538 – 1550, 2005.

[57] Bo Lu ; Shahidehpour, M. “Unit commitment with flexible generating units”, Power Systems, IEEE Transactions on Volume: 20 , Issue: 2, Page(s): 1022 – 1034, 2005.

[58] Zuyi Li ; Shahidehpour, M. “Security-constrained unit commitment for simultaneous clearing of energy and ancillary services markets”, Power Systems, IEEE Transactions on Volume: 20 , Issue: 2, Page(s): 1079 – 1088, 2005.

[59] Xiaohong Guan ; Sangang Guo ; Qiaozhu Zhai, “The conditions for obtaining feasible solutions to security-constrained unit commitment problems”, Power Systems, IEEE Transactions on Volume: 20 , Issue: 4, Page(s): 1746 – 1756, 2005.

[60] Mitani, T. ; Mishima, Y. ; Satoh, T. ; Nara, K., “Security Constraints Unit Commitment by Lagrangian Decomposition and Tabu Search”, Systems, Man and Cybernetics, 2006. SMC '06. IEEE International Conference on Volume: 3, Page(s): 1843 – 1848, 2006.

[61] Collett, R. ; Quaicoe, J., “Security-Constrained Unit Commitment using Particle Swarms”, Electrical and Computer Engineering, 2006. CCECE '06. Canadian Conference, Page(s): 1125 – 1129, 2006.

[62] Yong Fu ; Shahidehpour, M. ; Zuyi Li, “AC contingency dispatch based on security-constrained unit commitment”, Power Systems, IEEE Transactions on Volume: 21, Page(s): 897 – 908, 2006.

[63] Lei Wu ; Shahidehpour, M. ; Tao Li, “ Stochastic Security-Constrained Unit Commitment”, Power Systems, IEEE Transactions on Volume: 22 , Issue: 2, Page(s): 800 – 811, 2007.

[64] Zhaoqiang Ge ; Ying Cao , “Security constrained unit commitment for East China Electric Power Market”, Electric Utility Deregulation and Restructuring and Power Technologies, IEEE. DRPT 2008. Third International Conference, Page(s): 218 – 221, 2008.

[65] Askarpour, M. ; Zeinadini, V. “Security-constrained unit commitment reaction to load and price forecasting errors”, Energy Market, IEEE. EEM 2009. 6th International Conference on the European Publication, Page(s): 1 – 7, 2009.

[66] Yong Fu ; Zuyi Li ; Shahidehpour, M. ; Tongxin Zheng ; Litvinov, E. “Coordination of Midterm Outage Scheduling With Short-Term Security-Constrained Unit

Commitment", Power Systems, IEEE Transactions on Volume: 24 , Issue: 4, Page(s): 1818 – 1830, 2009.

[67] Bozorg, M. ; Hajipour, E. ; Hosseini, S.H., "Interruptible load contracts implementation in stochastic security constrained unit commitment", Probabilistic Methods Applied to Power Systems (PMAPS), 2010 IEEE 11th International Conference, Page(s): 796 – 801, 2010.

[68] V. Senthil Kumar, , M.R. Mohan "Solution to security constrained unit commitment problem using genetic algorithm", Department of Electrical and Electronics Engineering, College of Engineering Guindy, Anna University, Chennai 600 025, India, International Journal of Electrical Power & Energy Systems Volume 32, Issue 2, Pages 117–125, February 2010.

[69] Qiaozhu Zhai ; Xiaohong Guan ; Jinghui Cheng ; Hongyu Wu, "Fast Identification of Inactive Security Constraints in SCUC Problems", Power Systems, IEEE Transactions on Volume: 25 , Issue: 4, Page(s): 1946 – 1954, 2010.

[70] Chakraborty, S. ; Senjyu, T. ; Yona, A. ; Funabashi T., "Security constrained unit commitment strategy for wind/thermal units using Lagrangian relaxation based Particle Swarm Optimization", IPEC, 2010 Conference Proceedings, Page(s): 549 – 554, 2010.

[71] Lotfjou, A. ; Shahidehpour, M. ; Yong Fu ; Zuyi Li "Security-Constrained Unit Commitment With AC/DC Transmission Systems" Power Systems, IEEE Transactions on Volume: 25 , Issue: 1, Page(s): 531 – 542, 2010.

[72] Khodaei, A. ; Shahidehpour, M., "Transmission Switching in Security-Constrained Unit Commitment", Power Systems, IEEE Transactions on Volume: 25 , Issue: 4, Page(s): 1937 – 1945, 2010.

[73] Laothumyingyong, N. ; Damrongkulkamjorn, P., "Security-constrained unit commitment using Mixed-Integer Programming with Benders Decomposition", Electrical Engineering/Electronics Computer Telecommunications and Information Technology (ECTI-CON), 2010 International Conference, Page(s): 626 – 630, 2010.

[74] Qiaozhu Zhai ; Hongyu Wu ; Xiaohong Guan "Analytical conditions for determining feasible commitment states of SCUC problems" Power and Energy Society General Meeting, 2010 IEEE, Page(s): 1 – 8, 2010.

[75] Nima Amjady, Hadi Nasiri-Rad , "Security Constrained Unit Commitment by a new adaptive hybrid stochastic search technique", Original Research Article Energy Conversion and Management, Volume 52, Issue 2, Pages 1097-1106, February 2011.

[76] J.K. c, M.K. Kimb, Y.T. Yoona, J.K. Parka, "A new approach to security-constrained generation scheduling of large-scale power systems with a piecewise linear ramping model", International Journal of Electrical Power & Energy Systems Volume 34, Issue 1, Pages 121–131, January 2012.

[77] Nima Amjadya & Mohammad Reza Ansaria "Security-constrained Unit Commitment Considering Hydro Units and AC Network Modeling by a New Hybrid Solution

Method Composed of Benders Decomposition and Outer Approximation", Electric Power Components and Systems, Taylor & Francis Volume 40, Issue 13, 2012.

[78] Columbus, C.C., Simon, S.P. "Hybrid Particle swarm approach for Security constrained unit commitment" Computing, Electronics and Electrical Technologies (ICCEET), 2012 International Conference, Page(s): 128 – 133, March 2012.

[79] Papavasiliou, A. ; Oren, S.S., "A comparative study of stochastic unit commitment and security-constrained unit commitment using high performance computing", Control Conference (ECC), Page(s): 2507 – 2512, 2013.

[80] Alemany, J. ; Moitre, D. ; Magnago, F., "Benders Decomposition applied to Security Constrained Unit Commitment", Latin America Transactions, IEEE (Revista IEEE America Latina) Volume: 11 , Issue: 1, Page(s): 421 – 425, 2013.

[81] Yong Fu ; Zuyi Li ; Lei Wu, "Modeling and Solution of the Large-Scale Security-Constrained Unit Commitment", Power Systems, IEEE Transactions on Volume: 28 , Issue: 4, Page(s): 3524 – 3533, 2013.

[82] M. Karami, H.A. Shayanfar, J. Aghaei, A. Ahmadi, "Scenario-based security-constrained hydrothermal coordination with volatile wind power generation", Review Article Renewable and Sustainable Energy Reviews, Volume 28, Pages 726 – 737, December 2013.

[83] Mahdi Samiee, Nima Amjady, Hossein Sharifzadeh, "Security constrained unit commitment of power systems by a new combinatorial solution strategy composed of enhanced harmony search algorithm and numerical optimization", Original Research Article International Journal of Electrical Power & Energy Systems, Volume 44, Issue 1, Pages 471 – 481, January 2013.

[84] Bertsimas, D. ; Litvinov, E. ; Sun, X.A. ; Jinye Zhao ; Tongxin Zheng, "Adaptive Robust Optimization for the Security Constrained Unit Commitment Problem", Power Systems, IEEE Transactions on Volume: 28 , Issue: 1, Page(s): 52 – 63, 2013.

[85] Mollahassani-pour, M. ; Abdollahi, A. ; Rashidinejad, M., "Investigation of Market-Based Demand Response Impacts on Security-Constrained Preventive Maintenance Scheduling" Systems Journal, IEEE Volume: PP , Issue: 99, Article#: 1, 2014.

[86] Kargarian A. ; Fu, Y. ; Li, Z., "Distributed Security-Constrained Unit Commitment for Large-Scale Power Systems", Power Systems, IEEE Transactions on Volume: PP , Issue: 99, Page(s): 1 – 12, 2014.

[87] Bigdeli, M. ; Karimpour, A., "Optimal reserve requirements and units schedule in contingency Constrained Unit Commitment", Environment and Electrical Engineering (EEEIC), 2014 14th International Conference, Page(s): 443 – 448, 2014.

[88] Chen, L.Y. ; Li, Z.Y., "Optimal reserve dispatch and security-constrained unit commitment considering volatile wind", TENCON 2013 - 2013 IEEE Region 10 Conference (31194), Page(s): 1 – 6, 2014.

[89] Mohammad Reza Norouzi, Abdollah Ahmadi, Ali Esmaeel Nezhad, Amir Ghaedi, "Mixed integer programming of multi-objective security-constrained hydro/thermal

unit commitment", Review Article Renewable and Sustainable Energy Reviews, Volume 29, Pages 911 – 923, January 2014.

[90] Azza A. ElDesouky, "Security constrained generation scheduling for grids incorporating wind, photovoltaic and thermal power", Original Research Article Electric Power Systems Research, Volume 116, Pages 284 – 292, November 2014.

[91] Mir Mohammad Reza Sahebi, Seyed Hamid Hosseini, "Stochastic security constrained unit commitment incorporating demand side reserve", Original Research Article International Journal of Electrical Power & Energy Systems, Volume 56, Pages 175 – 184, March 2014.

[92] Ming Zhou, Shu Xia, Gengyin Li, Xiao Han, "Interval optimization combined with point estimate method for stochastic security-constrained unit commitment", Original Research Article International Journal of Electrical Power & Energy Systems, Volume 63, Pages 276 – 284, December 2014.

[93] Ehsan Nasrolahpour, Hassan Ghasemi, "A stochastic security constrained unit commitment model for reconfigurable networks with high wind power penetration", Original Research Article Electric Power Systems Research, Volume 121, Pages 341 – 350, April 2015.

[94] J. Alemany, F. Magnago, "Benders decomposition applied to security constrained unit commitment: Initialization of the algorithm", Original Research Article International Journal of Electrical Power & Energy Systems, Volume 66, Pages 53 – 66, March 2015.

[95] S. Sreejith, Sishaj P. Simon, M.P. Selvan, "Analysis of FACTS devices on Security Constrained Unit Commitment problem", Original Research Article International Journal of Electrical Power & Energy Systems, Volume 66, Pages 280 – 293, March 2015.

[96] A.I. Cohen and M. Yoshimura, "A branch and bound algorithm for unit commitment", IEEE Trans. Power Syst., Vol. PAS-101, pp. 222-451, 1982.

[97] W.L. Snyder, H.D. Powell and C. Rayburn, "Dynamic programming approach to unit commitment", IEEE Trans. Power Syst., Vol. PWRS-2, pp. 339-350, May 1987.

[98] Cohen. A.I and Sherkat. V.R, Optimization based methods for operations scheduling, Proceedings of IEEE, vol. 75, No. 2, pp. 1574-1591, Dec. 1987.

[99] Salam. S., Unit commitment solution methods, World academy of science, engineering and technology, vol.35, pp. 320-325, 2007.

[100] Tong. S.K and Shahidehpour. S.M, Combination of lagrangian-relaxation and linear programming approaches for fuel-constrained unit commitment problems, IEE Proc.-Gener. Transm. Distrib., vol. 136, No. 3, pp.162-174, May 1989.

[101] Swarup, K.S. and Yamashiro, S., "Unit commitment solution methodology using genetic algorithm", IEEE Transactions on Power Systems, vol. 17, issue 1, pp. 87-91, Feb. 2002.

[102] H.H. Balci and J.F. Valenzuela, "Scheduling electric power generation using particle swarm optimization combined with lagrangian relaxation method", Int. J. Appl. Math. Comput. Sci., Vol. 14, No. 3, 2004.

[103] Grzegorz Dudek, "Adaptive simulated annealing schedule to the unit commitment problem", Electric Power Systems Research, Volume 80, Issue 4, Pages 465–472, April 2010.

[104] A.H. Mantawy, Y.L. Youssef, L. Abdel-Magid, S.Z. Shokri and Z. Selim, "A unit commitment by Tabu Search", Proc. Inst. Inst. Elect. Eng. Gen. Trans. Dist., vol. 145, no.1, pp. 56-64, 1998.

[105] J.A. Momoh and J.Z. Zhu, "Optimal generation scheduling based on AHP/ANP", IEEE Trans. On Systems, Man and Cybernatics-Part B:, Vol. 33, No. 3, June 2003.

[106] Juste, K.A.;Kita, H.;Tanaka, E.;Hasegawa, J.," An evolutionary programming solution to the unit commitment problem", IEEE Transactions on Power Systems, Vol. 14, Issue 4, pp. 1452 – 1459, 1999.

[107] Columbus, Christopher C. and Simon, Sishraj P., "Hybrid Particle swarm approach for Security constrained unit commitment", Proc. of 2012 International Conference on Computing, Electronics and Electrical Technologies (ICCEET), pp. 128-133, 2012.

[108] Grey, A. and Sekar, A., "Unified solution of security-constrained unit commitment problem using a linear programming methodology", IET Genr. Trans. and Distr., vol. 3(2), pp. 182-197, 2007.

[109] Fu Y., Shahidehpour M. & Li Z., "Security-constrained unit commitment with AC constraints", IEEE Trans. Power Syst., vol. 21, pp. 897-908, 2006.

[110] Juan M. Ramirez & Pablo E. Oñate, "The Short-Term Hydrothermal Coordination via Genetic Algorithms", Cinvestav-Unidad Guadalajara, Taylor & Francis, Feb 2007.

[111] Chhetri, R. ; Venkatesh, B. ; Hill, Eugene F., "Security Constraints Unit Commitment for a Multi-Regional Electricity Market", Power Engineering, 2006 Large Engineering Systems Conference, Page(s): 47 – 52, 2006.

[112] M. Afkousi-Paqaleh , M. Rashidinejad, M. Pourakbari-Kasmaei "An implementation of harmony search algorithm to unit commitment problem" Electrical Engineering, springer link, Volume 92, Issue 6, pp 215-225, November 2010.

[113] Zeynal, H.; Lim Xiao Hui; Jiazhen, Y.; Eidiani, M.; Azzopardi, B. "Improving Lagrangian Relaxation Unit Commitment with Cuckoo Search Algorithm" Power and Energy (PECon), 2014 IEEE International Conference, Pages: 77 – 82, 2014.

[114] K. Chandrasekaran, , Sishaj P. Simon "Multi-objective scheduling problem: Hybrid approach using fuzzy assisted cuckoo search algorithm" Department of Electrical and Electronics Engineering, National Institute of Technology, Tiruchirappalli-620015, Tamil Nadu, India, Elsevier, January 2012.

[115] Alireza Gharegozi, Rozbeh Jahani “A New Approach for Solving the Unit Commitment Problem by Cuckoo Search Algorithm” Affiliations Shahindezh Branch, Islamic Azad University, Shahindezh, Iran, Islamic Republic, October 2013.